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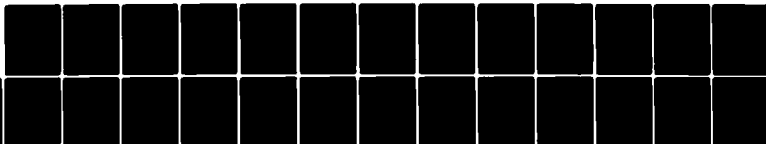
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PHILADELPHIA HAFTER VISION RES... J B SIEGFRIED

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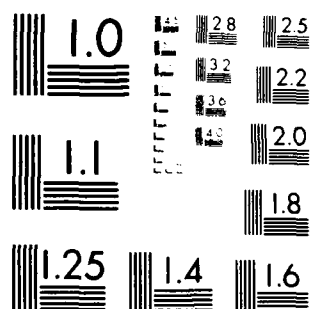
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Previous research by the author had demonstrated that the spectral sensitivity of the visual system as measured by the visual evoked potential from the human scalp exhibited discrepancies from the spectral sensitivity function as measured by psychophysical techniques. These discrepancies were in the short wavelength ("blue") region of the visible spectrum. Such discrepancies were explained by the discovery that blue lights evoked cortical potentials with longer latencies and implicit times than lights which stimulate the middle and long wavelength sensitive mechanisms. The current research deals with a further elucidation		

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tion of this finding, by studying the fast wavelets ("oscillatory potentials") arising in the retina and measured by means of the electroretinogram. High frequency wavelets were also observed at the scalp in the visual evoked potential.

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## I. STATEMENT OF THE PROBLEM

Past research by the author indicated that certain anomalies were present in the spectral sensitivity of the visual evoked potential (VEP) recorded from the scalp overlying the occipital (visual) cortex. It was demonstrated that these anomalies arose from alterations in the latency, or implicit time of VEP responses generated by visual stimuli which stimulated primarily the short wavelength sensitive mechanism ("blue"). Latencies of this short wavelength sensitive mechanism were shown to be longer than those of the middle and long wavelength sensitive mechanisms. This problem was to be further studied by means of Electroretinographic (ERG) recordings under similar conditions. In order to make the measurements of small electrical potentials more reliable, attention was paid to high frequency wavelets (100 to 150 Hz), whose latencies and implicit times could be measured very precisely.

## II. SUMMARY OF THE MOST IMPORTANT RESULTS

1. ERG spectral sensitivity differs from VEP spectral sensitivity, as measured by the implicit time of high frequency wavelets, but mostly in a manner consistent with the effects of stray light on the retina, and the heavy dependence of the VEP upon the fovea.
2. The electrophysiological recording of high frequency wavelets at the retina and cortex is facilitated by bandpass filtering between limits of 50 and 250 Hz.
3. The application of post hoc digital filtering to the averaged electroencephalic data eliminates the distortion of amplitude and phase common with online analog filtering.
4. The high frequency wavelets recorded at the retina (ERG) are of a higher repetition frequency (approximately 140 Hz) than those recorded at the cortex (VEP) (approximately 100 Hz. for flash, and 50 Hz for pattern reversal stimulation).
5. VEP wavelets are recorded more efficiently and more easily than ERG wavelets, since stray light on the retina is not as much of a problem for Cortical VEP recordings. This is the case because the VEP from the scalp is heavily dependent upon stimulation of the fovea, and is relatively insensitive to stimulation of the retinal periphery.

## III. PUBLICATIONS

- Whittaker, S. G. & Siegfried, J. B. Origins of wavelets in the visual evoked potential (VEP). The EEG Journal, 1983, 55, 91-101.
- Siegfried, J. B. Analog vs digital filtering techniques utilizing microprocessors. Documenta Ophthalmology Proceedings Series, 1983 (in press).
- Whittaker, S. G. & Siegfried, J. B. Origins of wavelets in the VEP. Investigative Ophthalmology & Visual Science, 1982, 11, 283.

IV. PARTICIPATING SCIENTIFIC PERSONNEL

John B. Siegfried, Ph.D., Principal Investigator

Stephen G. Whittaker, Ph.D. (no salary)

Eileen S. Klitsch, Ph.D. (no salary)

No degrees were earned during this contract.

V. OTHER

Technical details of the projects accomplished during this contract are contained in the publication and manuscript attached to this REPORT.

VI. APPENDIX

Reprint, Whittaker, S. G. & Siegfried, J. B. Origins of wavelets in the visual evoked potential (VEP). The EEG Journal, 1983, 55, 91-101.

Reprint, Whittaker, S. G. & Siegfried, J. B. Origins of wavelets in the VEP Investigative Ophthalmology & Visual Science, 1982, 11, 283.

Manuscript, Siegfried, J. B. Analog vs digital filtering techniques utilizing microprocessors. Documenta Ophthalmologica Proceedings Series, 1983 (in press).

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# DIGITAL VS ANALOG FILTERING OF ELECTROPHYSIOLOGICAL DATA UTILIZING MICROPROCESSORS

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## ABSTRACT

Digital filtering of averaged evoked potential waveforms by microprocessor is presented and evaluated as a technique for enhancement of signal-to-noise ratio, and compared to analog filtering. It is shown that analog filters inherently produce distortions of amplitude and phase, and that these distortions are virtually eliminated within the bandpass limits of a digital filter. Calibration data are presented, comparing phase and amplitude before and after both analog and digital filtering. Digital filtering is accomplished offline by means of an LSI-11 microprocessor. In addition, filtering effects upon actual data are shown and analysed.

## INTRODUCTION

Analog filtering of electrophysiological visual signals is commonly employed to improve signal-to-noise ratios, as a low pass filter to attenuate high frequency noise, as a band reject or "notch" filter to attenuate house mains interference, and as a bandpass filter to selectively enhance "wavelets" ("oscillatory potentials") and other medium frequency phenomena (Siegfried and Lukas, 1981 a, b; Siegfried and Whittaker, 1982; Whittaker and Siegfried, 1982).

1

The use of analog filters, whether "passive" as are found in most amplifiers, or "active" produces predictable distortions of the electrophysiological data both in amplitude and phase. The steeper the slopes of the analog filter, the more extensive and significant the distortion. With passive analog filters set to a 1-1000 Hz passband, with the usual shallow slopes associated with amplifier filters, probably little significant distortion occurs within the frequency range of interest. However, when relatively narrow bandpass filtering is performed, for example 50-200 Hz to selectively enhance 100 Hz wavelets, significant phase distortion occurs. This means that latency or implicit time measurements may be seriously in error. Digital filtering by microprocessor represents another technique to improve signal-to-noise ratios. I calibrated the electrical recording system using sine wave input of various frequencies and analysed the effects of both active analog filtering and digital filtering. In addition, the effects on actual data are presented.

#### METHODS

1.73 V rms sine waves were applied as input to a signal averaging computer (Nicolet Instruments Corp., model 1174), both directly and through an active analog filter (Krohn-Hite, model 3323). The filter was set for a bandpass of 50-200 Hz, -3 dB points, 24 dB/octave slopes. The input to the signal averaging computer was filtered with a passive 2KHZ low pass analog filter. Sampling rate was 40,960 Hz.

Digital filtering was performed upon the averaged data, and was processed after averaging by a microprocessor (Digital Equipment Corp., MINC



11/23). First, the average was subjected to a forward fast Fourier transform (FFT) (Cooley and Tukey, 1965). This procedure yielded a real and imaginary set of 4096 coefficients, corresponding to frequencies, where  $\text{frequency} = (\text{Fourier coefficient})/(\text{epoch})$ . Second, those coefficients corresponding to frequencies outside the bandpass of interest (in this case, 50-200 Hz) are set to zero. And third, an inverse FFT is performed by the computer. This last process returns the data from frequency domain to temporal domain. The data now consists of only those frequencies between 50 and 200 Hz.

#### RESULTS AND DISCUSSION

Figure 1 shows the original sine wave input ("unfiltered", left column), for frequencies from 20 Hz to 680 Hz, and after filtering, both analog (middle column) and digital (right column). Bandpass is 50-200 Hz for both analog and digital filters. Each record is 100 ms in duration, and amplitude scales are the same for all records. Figure 2 shows plots of amplitude attenuation and phase shift for both analog and digital filtering. Two points should be noted which are illustrated in Figures 1 and 2. The digital filter is much more sharply defined, being essentially rectangular, and the analog filter exhibits very significant phase shifts, both phase advance and phase lag. Even when the analog filter bandpass settings are selected to cause zero phase shift at a particular frequency (in this case, 100 Hz, the approximate repetition frequency of cortical VEP wavelets), very significant phase shifts occur with small increases and decreases in frequency from this value.

Figure 3 illustrates the effect of analog and digital filtering upon VEP wavelet recordings. The original averaged waveform is seen in the top record (A) in which wavelets are seen superimposed on early slow waves,

preceding and coincident with "P100". In B, records have been digitally filtered 50-200 Hz. It can be seen that in the digitally filtered records, wavelet peaks line up precisely with those seen in the original records (A), while slow waves have been attenuated. In C, records have been active analog filtered. Wavelet peak phase shifts, equivalent to as much as 10 ms are evident from a visual inspection of the records.

One serious pitfall of digital filtering should be carefully noted. "Windowing" artifacts may be easily created due to the implicit iterative assumption of the FFT algorithm. Such effects manifest themselves as damped oscillations at the beginning and end of the digitally filtered record if they are present. They are caused by any differences in d.c. level or slope of the averaged waveform between the first few data points at the beginning of the record and the last few data points at the end of the record. (Theoretically, the data should begin and end at zero). In order to virtually eliminate this artifact, the averaging sampling "epoch" has been adjusted to precisely equal the inter-stimulus onset interval, and the inter-stimulus interval is relatively long (500 ms). This forces the averaged VEP waveform to be the same at the beginning and end of the "window". In Figure 1, windowing artifacts have been eliminated by carefully matching up the beginning and end of each sine wave input function.

In summary, all recording systems should be calibrated in order to analyse distortions of amplitude and phase. Such distortion is minimal for relatively wide analog bandpass limits and shallow slopes such as are found in most physiological amplifiers. However, when the need for relatively narrow bandpass filtering, or low- or high-pass filtering arises, other solutions may be sought. Active analog filters offer more selectivity, in terms of steeper slopes and narrower bandpass limits, but they introduce

significant distortions. One solution, which is relatively simple to implement on a microprocessor, is digital filtering. This has the advantage of introducing zero phase and amplitude distortion within the domain of the filter bandpass.

## FIGURE LEGENDS

FIGURE 1: Sine wave calibration of recording system. Each record is the average of 64 sweeps, of 100 ms duration. Amplitude scale is constant throughout the figure. Left column is sine wave input. Middle column has passed through an active analog filter set at 50-200 Hz, -3 dB points, 24 dB/octave slopes. Right column has been digitally filtered 50-200 Hz.

FIGURE 2: Amplitude attenuation (A) and phase angle (B) as functions of frequency for the calibration data presented in Figure 1. Positive phase angles represent phase advance; negative phase angles represent phase lag.

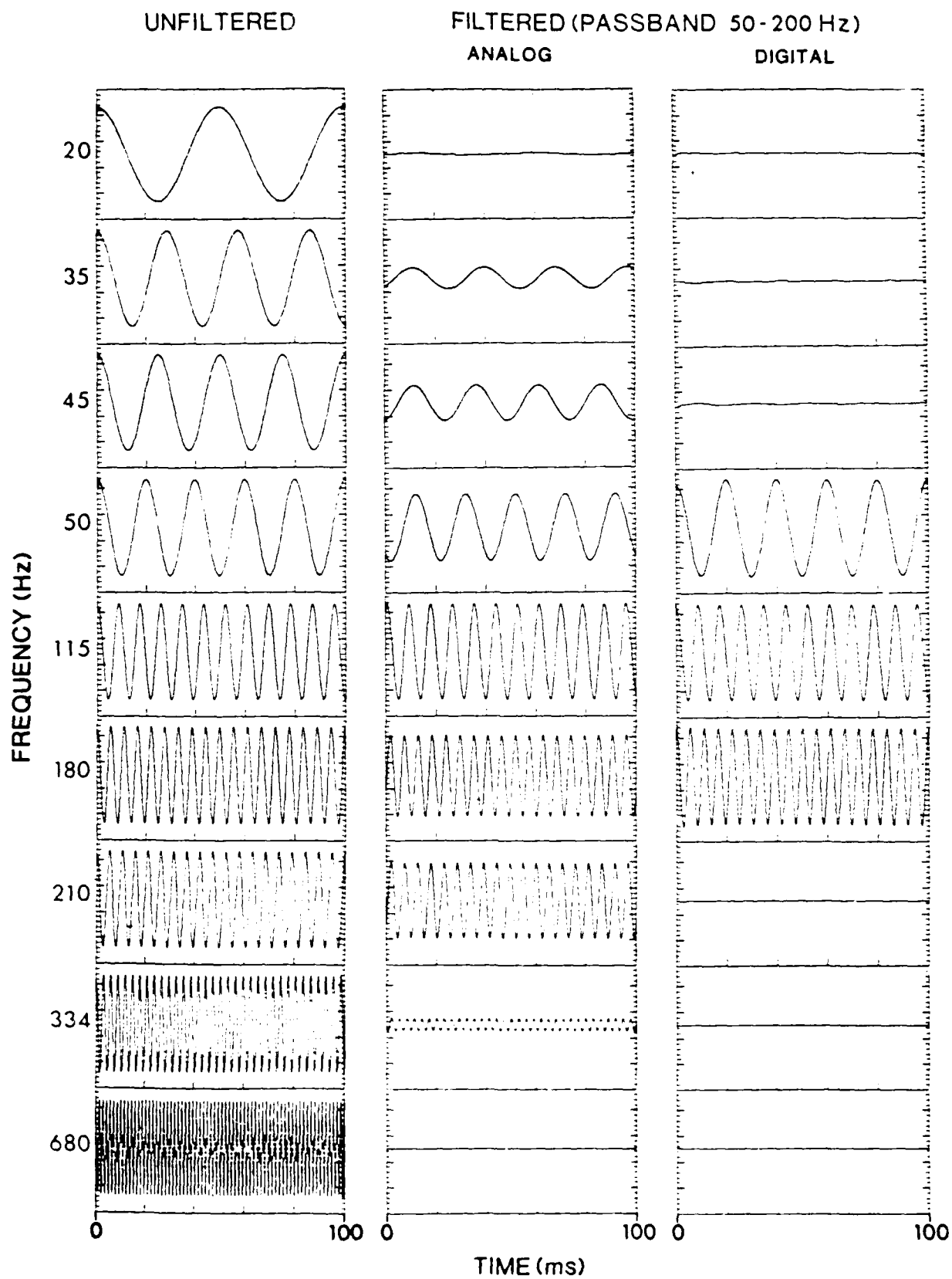
FIGURE 3: (A) Two consecutive averages of 256 sweeps superimposed passed through 1-1000 Hz passive analog filter. 20 ms flash duration onset coincident with beginning of record, 2 Hz flash repetition rate. Positivity at the occipital electrode ( $O_z$ ) relative to reference ( $C_z$ ) is indicated by an upward deflection. (B). Record A after digital filtering 50-200 Hz. (C). Record A after active analog filtering 50-200 Hz, -3 dB points, 24 dB/octave slopes. Initial sampling rate is 8,192 Hz. Computer input low pass filter setting was 2 kHz.

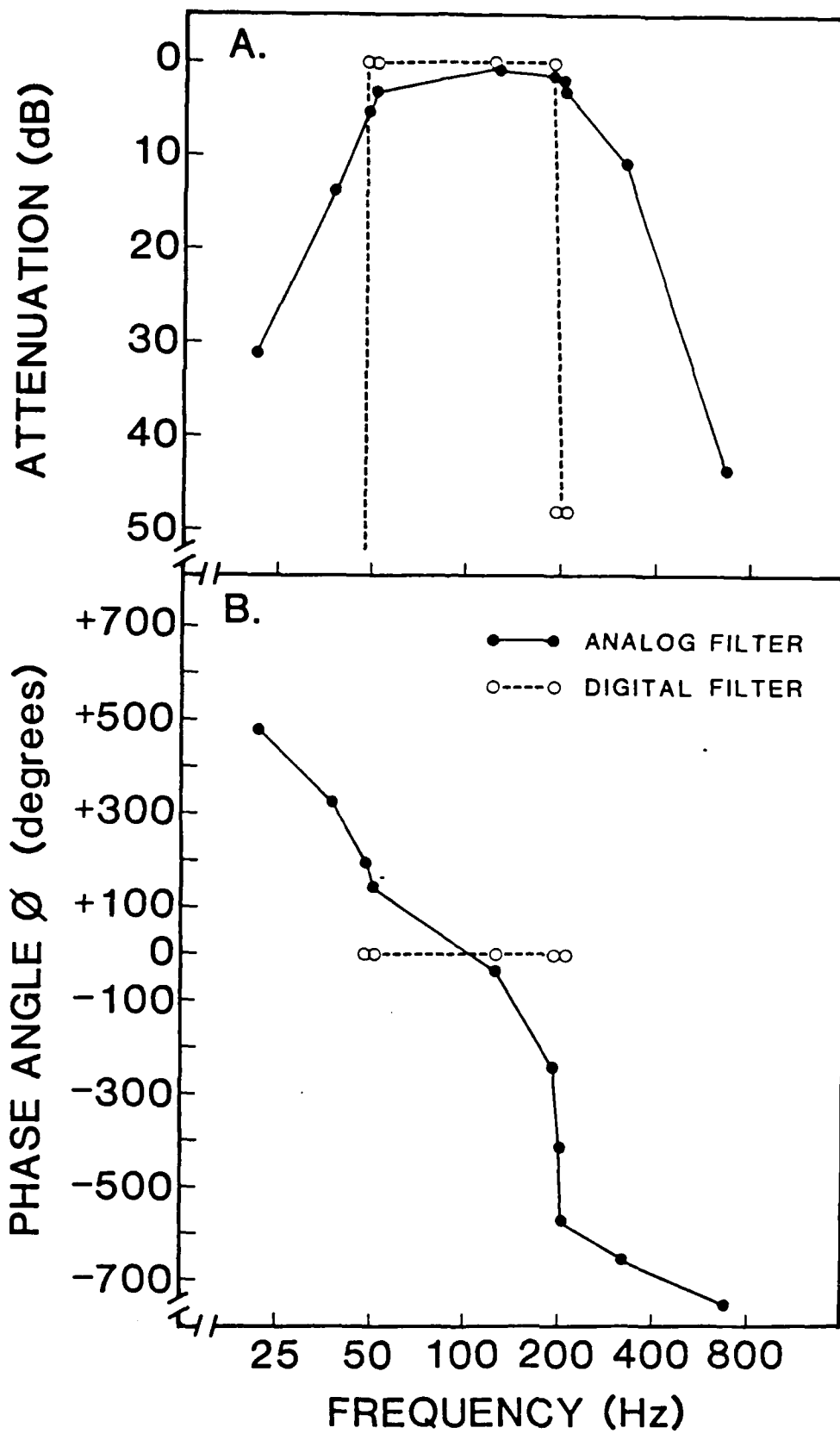
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5. Whittaker, S.G. and Siegfried, J.B. Origin of wavelets in the visual evoked potential. Electroencephalography and Clinical Neurophysiology, 1982 (in press).

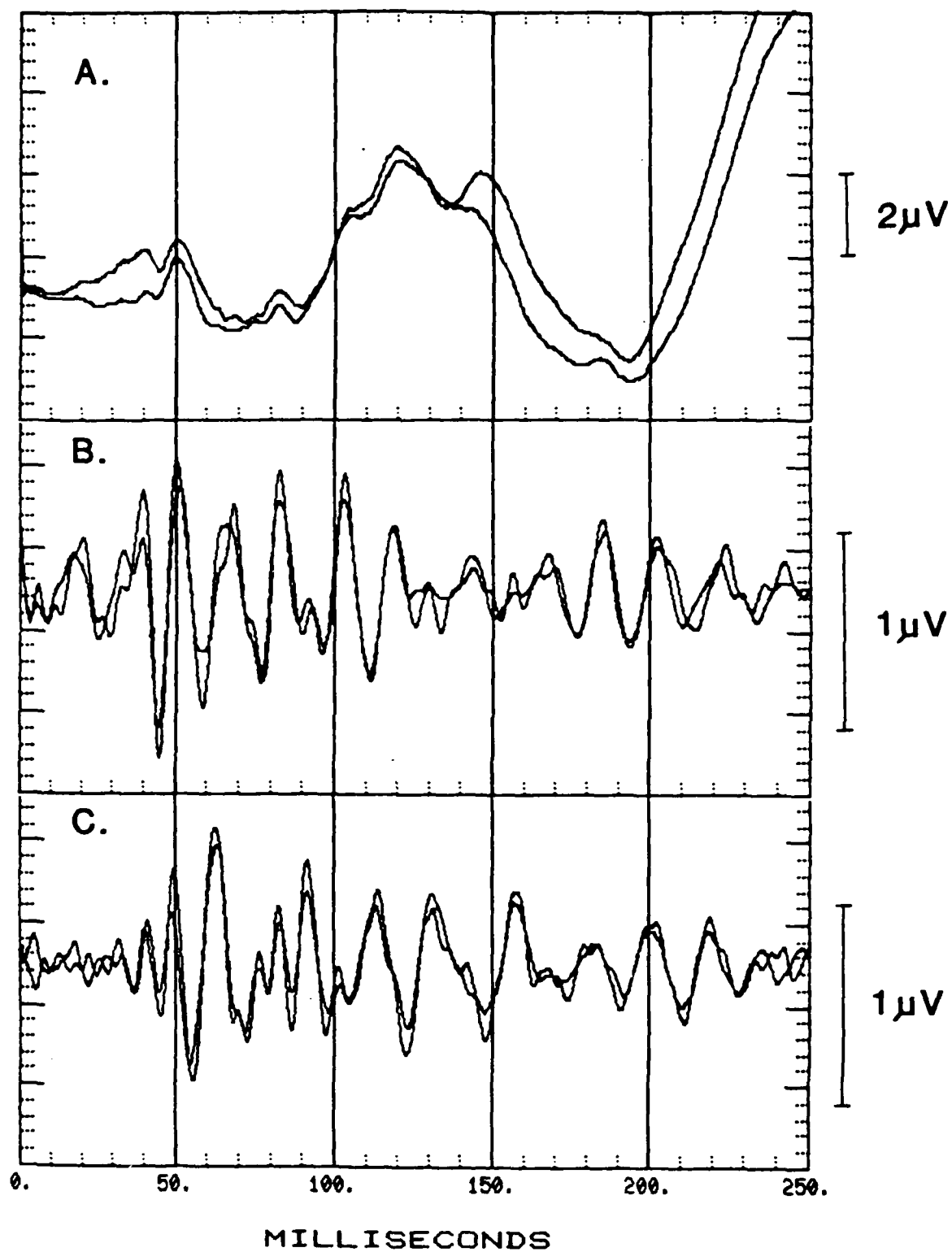
## ACKNOWLEDGEMENT

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AMPLITUDE





## ORIGIN OF WAVELETS IN THE VISUAL EVOKED POTENTIAL<sup>1</sup>

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(Accepted for publication: August 23, 1982)

Small amplitude, relatively high frequency wavelets (also called 'oscillations,' 'oscillatory potentials,' 'ripples') have been demonstrated to be ubiquitous in the visual system of animals (Doty and Kimura 1963; Hughes 1964; Steinberg 1966; Wachtmeister and Dowling 1978). They are also observed at the level of the retina in human electroretinogram (ERG) grossly recorded from the cornea or from the skin about the eye. From research on the origins of these wavelets in the retina, Wachtmeister and Dowling (1978) have found that various wavelets arise from distinct locations of the inner nuclear layer of the retina.

In human recordings from electrodes affixed to the scalp, little attention has been given to the relatively high frequency end of the recording spectrum. Most of the visual evoked potentials (VEPs) appear at relatively low frequencies as usually selected by the setting of filters. Nevertheless, some published records (Cobb and Dawson 1960; Allison et al. 1977) exhibit small wavelets superimposed upon the large slow waves obtained from scalp electrodes, most visibly from the area over the visual cortex. Rather than filter out higher EEG frequencies, Cracco and Cracco (1978) tuned analog filters to pass frequencies greater than 100 Hz. In these records wavelets were quite salient and diffuse over the scalp. The origin of these early and diffuse wavelets, however, was not established.

It is important to rule out ERG potentials as the origin of these VEPs. Because wavelets have

short latencies and have amplitudes of usually less than 1  $\mu$ V, they are especially prone to contamination by volume conducted retinal potentials which can reach over 500  $\mu$ V at the cornea. Early VEPs recorded in frontal scalp regions would be particularly prone to such contamination by the ERG. Siegfried and Lukas (1981) found that wavelets recorded between  $C_z$  and  $O_z$  differed in many respects from ERG wavelets, and that they occurred somewhat later than the earliest wavelets reported by Cracco and Cracco (1978).

In some recent experiments, early VEP components suspected to be of subcortical origin were recorded from temporal scalp locations (Rubenstein and Harding 1981). Cracco and Cracco (1978) attached the 'reference' electrode to the ear ipsilateral to the stimulated eye, in the region where Rubenstein and Harding (1981) found early VEPs. It cannot be ruled out that Cracco and Cracco's results reflected VEPs of diverse origins including retinal and subcortical potentials.

Another problem is the measurement of early VEPs. When the EEG is broadly filtered (1-1000 Hz bandpass) we have found that the earliest positive peak in the flash evoked potential has a peak latency of 90-130 msec. This peak, nominally 'P100,' has a duration of about 50 msec and an amplitude of 10-20  $\mu$ V.

The purposes of the present experiments were to develop methods for a reliable measurement of early VEPs and wavelets and to determine the probable origins of these early VEP components. In pursuit of the second objective we conducted a study of the topographical distribution of wavelets and P100 to determine (a) whether any part of early VEP components was passively conducted from the retina; (b) whether the topographical

<sup>1</sup> These experiments were supported by National Eye Institute Grant EY03467 and Department of the Army Research Contract No. DAAG29-79-C-0103 to John Siegfried.

distribution of wavelets was diffuse or centered over the visual cortex; and (c) whether wavelets and P100 were generated by different mechanisms. We also addressed these questions by varying the stimulus wave length and retinal illuminance and by comparing the effects of these stimulus variables on latencies of ERG wavelets, P100 and wavelets recorded at the occiput. We reasoned that evoked potentials that had different relations to stimulus variables would have different generators.

## Methods

Stimuli were projected into the right eye of a supine subject, in maxwellian view, and consisted of unpatterned homogeneous light flashes which subtended 25° visual angle. The stimuli were applied in an otherwise dark field of view. Either a dim red spot or an incomplete crosshairs aided in maintaining fixation of the eye. In all but the topography experiment (experiment II) recording electrodes were affixed to the scalp at occiput ( $O_2$ ) and vertex ( $C_z$ ) according to the International 10/20 system, and the subject ground was to linked ear lobes. All electrodes had impedances of less than 2000  $\Omega$  at 30 Hz.

Electrical activity was led off from the scalp through 24  $\mu$ A solid-state circuit breakers to a cascaded pair of preamplifiers (80 dB gain, 1-1000 Hz bandpass), and then out of the electrically shielded enclosure. The amplified signal was sent directly to one channel of a signal averager. In parallel, the amplified signal was also modified by active analog filters (40 dB gain, 60-200 Hz, 24 dB/octave rolloff) and sent to a second channel of the signal averager. The signal averager would reject input if, at any time during the recording epoch of 200 msec, 90% of the full scale voltage was exceeded. The full scale for the normally filtered input was usually 8  $\mu$ V and for the broadly filtered input, 25  $\mu$ V. If at some electrode positions, full scale voltages had to be increased because of excess artifact, then the number of epochs averaged was increased proportionally. As a result, standard error of mean peak amplitudes did not systematically change across electrode positions.

## Results

### *Experiment I. Illuminance effects on wavelets and P100 in 16 subjects*

In earlier reports wavelets were found to occur with a repetition rate of approximately 100 Hz which did not systematically vary (Siegfried and Lukas 1981). In the present experiment, we set active filters to a bandpass of 60-200 Hz and verified that no recording system distortion was present near 100 Hz.

To evaluate how consistently wavelets could be recorded across subjects, VEPs were recorded from each of 16 subjects over a range of  $10^{0.3}$ - $10^{4.0}$  trolands ( $10^{5.3}$  trolands in some subjects) retinal illuminance. The reliability, especially of the repetition rates of the wavelets, was evaluated both within and across subjects. We also compared relations between latencies of wavelets and P100, the earliest slow wave whose peak could be reliably measured at lower light intensities. If P100 and wavelets had common generators then one would expect similar relations between retinal illuminance and latency.

The results of varying retinal illuminance on both narrowly and broadly filtered VEPs are plotted for two subjects in Figs. 1 and 2. Wavelets seen as ripples on the slow waves of the broadly filtered VEPs were selectively enhanced by the narrowly tuned filters. Wavelets are present and clearly defined for subject J.W. (Fig. 1) even though the broadly filtered VEPs were of very small amplitude.

The earliest slow wave peak that could be reliably measured across subjects, with broadly tuned filters (1-1000 Hz), was a negative peak just preceding the highly reliable P100, and had a mean latency of 72 msec (S.D. = 12.34). Although earlier wavelets could be identified in broadly filtered VEPs, they did not replicate reliably in many subjects. Employing analog filtering enabled us to reliably identify a burst of from 4 to 10 wavelets over a range of  $10^{2.0}$ - $10^{4.0}$  trolands retinal illuminance in 15 out of 16 normal subjects. A  $10^{4.0}$  troland flash elicited the first identifiable wavelet at a mean peak latency of 39 msec across subjects (S.D. = 8.4). By using active analog filters, wavelets can thus be consistently measured in subjects with normal vision.

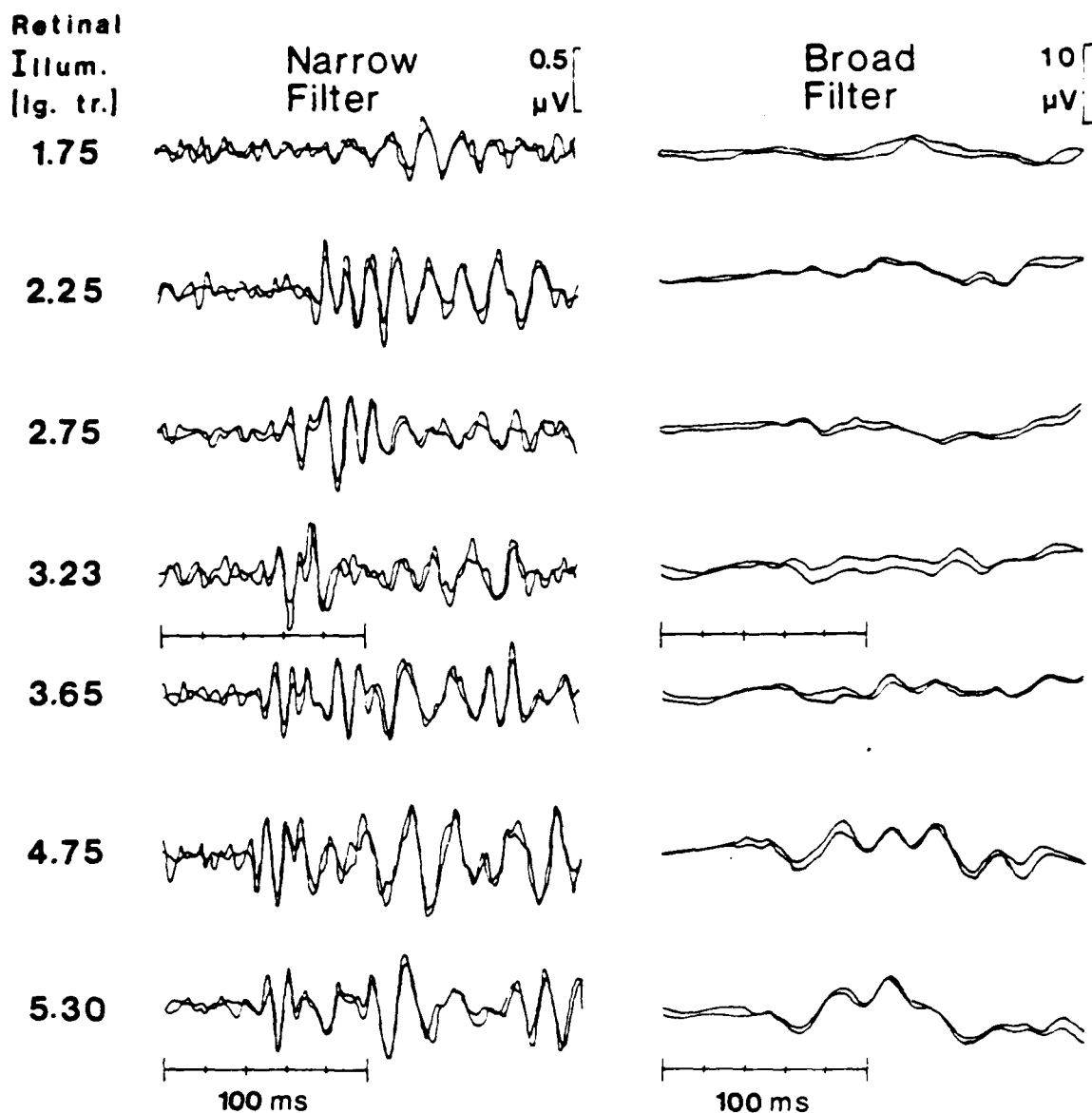


Fig. 1. VEPs (positive upward) evoked by a 100 msec, 25° visual angle flash of various retinal illuminances. 'Narrowly filtered' VEPs were averaged after EEG was passed through a 60–200 Hz active bandpass filter, whereas 'broadly filtered' VEPs were filtered by a more conventional 1–1 kHz bandpass. Ig. tr., retinal illuminance. Recorded from subject J.W. Flash onset occurs at the beginning of each tracing.

Having found that the wavelets are not idiosyncratic phenomena but rather highly consistent visual evoked potentials, we felt compelled to

search for the neurogenerators of these wavelets. Examination of the results of this normative study confirmed an earlier hypothesis that wavelets and

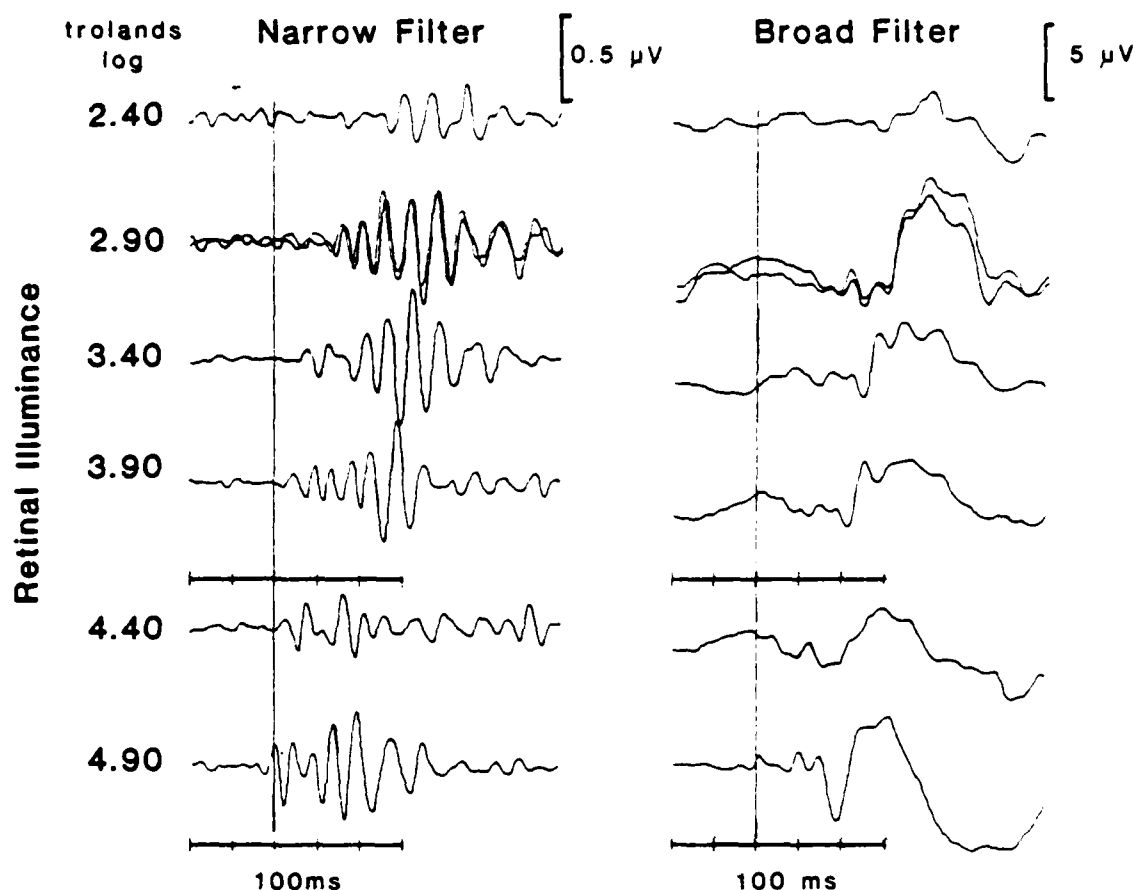


Fig. 2. VEPs (positive upward) evoked by a 100 msec, 25° visual angle flash of various retinal illuminances. See Fig. 1 for details. Recorded from subject J.H. Flash onset occurs at the beginning of each tracing.

early slow waves are not generated by a common source (Siegfried and Lukas 1981).

In Figs. 2 and 3 one can see that increasing retinal illuminance produced a decrease in the latencies of both wavelets and slow waves; however, as retinal illuminance increased above approximately  $10^{2.0}$  trolands, the slow wave latencies apparently reached asymptote. The wavelets, however, continued to occur with shorter latencies as retinal illuminance increased up to  $10^{4.0}$  trolands. This difference between slow waves and wavelets is better illustrated in Fig. 3 in which latencies of two adjacent wavelets and P100 are plotted as a function of retinal illuminance using data from 3

additional subjects. The difference between the illuminance relations of wavelets and P100 obtained by the present experiment confirms a similar report by Siegfried and Lukas (1981) that was based on data from one subject.

Fig. 3 also illustrates the constant inter-wavelet intervals for each subject which typify the invariance of the repetition rate of the wavelets while retinal illuminance was varied. The stability of the repetition rate throughout all of the experiments conducted in the present study permitted clear identification and labeling of individual wavelets which occurred before 80 msec in the data of an individual subject across experimental conditions.

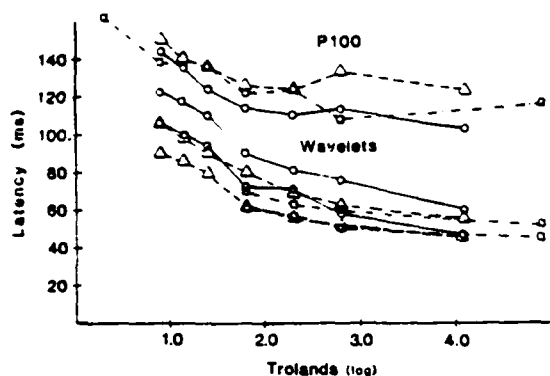


Fig. 3. Peak latency of two adjacent wavelets as a function of retinal illuminance. Data from 3 subjects, S.A.W. (triangles), J.B.S. (circles) and C.H. (squares) are plotted. Wavelets are from VEPs obtained after a 60–200 Hz active bandpass, whereas P100 is the first reliable positivity measured in the broadly filtered (1–1 kHz) VEP.

However, both the repetition rates and implicit times of wavelets appeared sufficiently different from subject to subject to preclude the identification of 'similar' wavelets across subjects on the basis of latency alone as is commonly done with more pronounced slow waves in the broadly filtered VEP.

#### Experiment II. Wavelet and P100 topography

We set out to examine two questions concerning the origin of VEP wavelets: (1) what is their relation, if any, to volume conducted ERG, and (2) are they generated by visual cortex, or are they largely the product of diffuse cerebral or subcortical events.

Siegfried and Lukas (1981) found that wavelets recorded at the occiput had significantly longer latencies than ERG wavelets and that the occipital wavelets had a different repetition rate as compared to the ERG wavelets. Thus, they ruled out the possibility that wavelets recorded at the occiput were exclusively volume conducted ERG. However, there might be a possibility that potentials volume conducted from the retina contribute to the wave form recorded from the scalp. We undertook a topographical study to assess this possible ERG contribution to the cortical wavelets.

We positioned the 'exploring' electrode laterally, along a line from the occiput, through  $T_3$  (or  $T_4$ ) and the nasion with a common reference electrode at  $C_z$  and ground to linked ear lobes (illustrated in Fig. 4). The exploring electrodes were placed apart at a constant distance, 16% of the occiput to nasion distance measured through  $T_3$ . The occiput ( $O_2$ ),  $T_3$ ,  $T_4$ ,  $C_z$  and the nasion were located according to the 10-20 system. As the position of the exploring electrode approaches the retina of the stimulated eye, the amplitude of retinal potentials should increase, and those potentials originating from visual cortex should decrease. Purportedly subcortical potentials have been recorded that reach a maximum amplitude close to  $T_3$  or  $T_4$  (Rubenstein and Harding 1981), in the region of our third lateral electrode placement ( $L_3$  and  $R_3$  in Fig. 4).

In order to more precisely locate the wavelet source, we also used a series of bipolar electrode pairs. The members of the pair of electrodes were positioned adjacently in the lateral series described above with the non-inverting differential amplifier input (+) always in the same direction (see Fig. 4). With this closely spaced electrode configuration, diffuse or subcortical potentials should become vanishingly small. As the electrodes approach one pole of a source with the non-inverting electrode closer, the potentials generated from that source should abruptly increase, and then decrease when the bipolar pair is located over the source. The potentials should then invert when the pair moves away from the source with the non-inverting electrode more distant (e.g. Regan 1972). For this topographical analysis, potentials were elicited with a flash frequency of 2 Hz. The retinal illuminance of the light was  $10^{4.0}$  trolands.

Visual evoked wavelets and broadly filtered VEP tracings are illustrated in Fig. 4 for the different lateral electrode positions in one subject. Latencies of relatively early wavelets (less than 75 msec) remain invariant over nearly the entire range of electrode loci where wavelets could be measured. This enabled us to define rather strict, objective criteria for measuring wavelet amplitude. The amplitude of a wavelet was included in the topographical analysis only if its peak was within 4 msec of the peak latency at its maximum am-

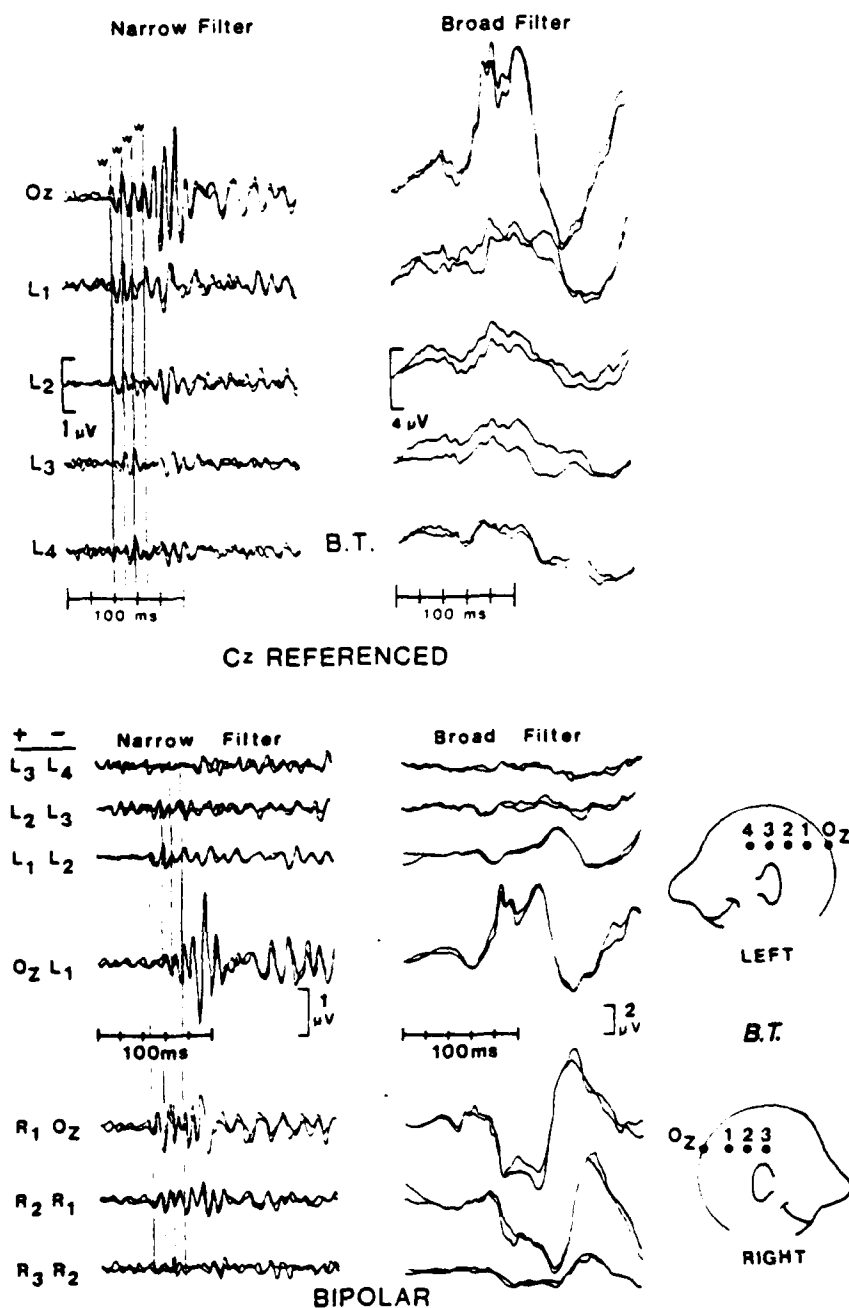


Fig. 4. Flash evoked potentials (positive upward) recorded at various lateral locations on the scalp of subject B.T. 'Narrowly filtered' VEPs were averaged after EEG was passed through a 60-200 Hz active bandpass filter. 'Broadly filtered' VEPs were filtered by a 1-1 kHz bandpass. Top: tracings resulted with the inverting (-) active electrode at C, and the non-inverting (+) active electrode at the various locations indicated. Bottom: tracings were recorded with inverting and non-inverting electrodes in adjacent lateral positions indicated. Flash onset occurs at the beginning of each tracing.

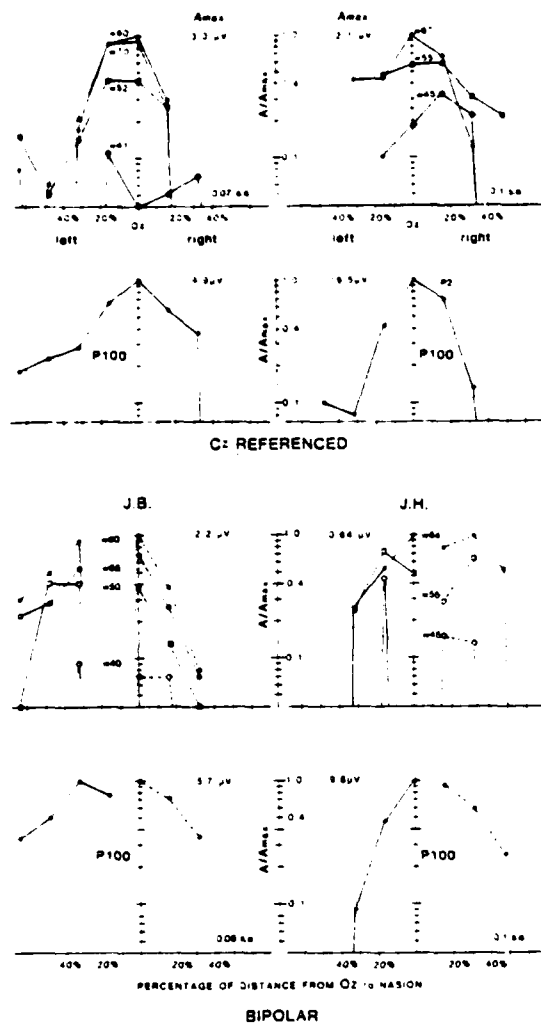


Fig. 5. Amplitude of wavelets (W40-W70) and P100 as a function of relative lateral distance from  $O_2$ . Wavelets were recorded following a 60-200 Hz active bandpass filter whereas P100 is a slow wave in the broadly filtered (1-1 kHz) VEP. Top 4 graphs were produced by placing the inverting (reference) electrode at  $C_2$  and non-inverting electrode at various lateral locations. Bottom (bipolar) 4 graphs were produced by placing the inverting and non-inverting electrodes in adjacent lateral positions. Lateral electrode positions are illustrated in Fig. 4. Amplitudes were normalized to the maximum peak amplitude in a series ( $A_{max}$ ) and plotted on logarithmic scale to preserve the shape of the relations across amplitude. Dashed line indicates a negative peak that was within 4 msec of a positive peak (solid line). Lines not terminated by a symbol indicate that a wavelet was not within the latency criterion at that location.

plitude, and only when it could be reliably replicated within 2 msec. It was not possible to develop such stringent criteria with the broadly filtered VEPs. With these wave forms, the first peak that could be reliably defined, P100, occurred at approximately 100 msec following light onset. Its latency varied considerably across electrode position (see Fig. 4) but was nevertheless defined as the peak closest to 100 msec. The amplitudes of wavelets and P100 were measured from the preceding peak of opposite polarity.

Fig. 4 shows the broadly and narrowly filtered VEPs measured at the various lateral locations. Included in this figure are both the  $C_2$  referenced series and the bipolar series of electrode configurations. Fig. 5 illustrates the relations between electrode locations and the amplitude of early wavelets and P100. The results of the  $C_2$  referenced series in Figs. 4 and 5 revealed a maximum amplitude for the wavelets adjacent to or at  $O_2$ , near but not necessarily at the same location at which P100 reached a maximum amplitude. These maxima correspond to the region where the polarities inverted when measured with closely spaced bipolar electrode pairs (Figs. 4 and 5). These relations between wavelet amplitude and electrode location are consistent with expectations if the wavelets are originating from visual cortex. If the wavelets represent diffuse cerebral or deep subcortical events, one would expect them to become unmeasurable (less than  $0.25 \mu V$  in our system) if the bipolar electrode pairs were placed close together. In the bipolar series of the present experiment, the wavelets were not reduced in amplitude in 1 of 3 subjects and were clearly measurable in the other two (Figs. 4 and 5) again indicating a spatially defined cerebral generator.

Rubenstein and Harding (1981) measured 'subcortical' potentials with a  $C_2$  reference in the region of the mastoid process near locations  $R_1$  and  $L_3$  (see Fig. 4), with latencies approximating 20-25 msec. Similar very early VEPs were not evident in our records. Some later wavelets increased in amplitude in the position closest to the stimulated eye in one subject (J.H. in Fig. 5) suggesting possible retinal or subcortical influence. However, the retinal and subcortical effects on the wavelets were generally slight, easily obscured by noise and the

more prominent cortical potentials.

In another topographical study, it was reported that early wavelets appeared over a larger region of the scalp (Cracco and Cracco 1978) leading these authors to suspect more subcortical involvement in wavelet genesis. In their experiment one electrode was 'referenced' to an ear while the others were attached according to the standard 10-20 system. However, the ear is by no means a neutral location with respect to VEPs. Indeed, VEPs around the ear referenced to more distant scalp locations (e.g.,  $C_z$ ) have been measured and are particularly sensitive to very early, possibly subcortical, activity (Rubenstein and Harding 1981). Cracco and Cracco also measured very early wavelets, beginning at approximately 20 msec. It is quite likely that their electrode configuration produced greater sensitivity to subcortical VEPs and retinal potentials. The electrode schema used in the present experiment appears to have provided more selective sensitivity to potentials generated by the visual cortex.

#### Experiment III. Spectral sensitivity of wavelets

Narrow band spectral flashes were used to elicit ERG and occipital VEP wavelets. At each of a number of wave lengths spanning the visible spectrum, an increasing illuminance series was employed to produce a function relating wavelet latency and retinal illuminance. Employing the criterion implicit time technique (Siegfried 1978) spectral sensitivity was calculated for both ERG and VEP wavelets simultaneously recorded and is plotted in Fig. 6. Analysis of the results indicated that VEP wavelet sensitivity followed the normal photopic function, as has been shown for VEP slow waves (Siegfried 1971). However, the ERG wavelet spectral sensitivity exhibited departures from the normal photopic function in the 'blue' region of the spectrum, in the direction of significantly greater sensitivity. Thus, the spectral sensitivity of cortical wavelets is clearly different from that of ERG wavelets measured simultaneously, under identical conditions.

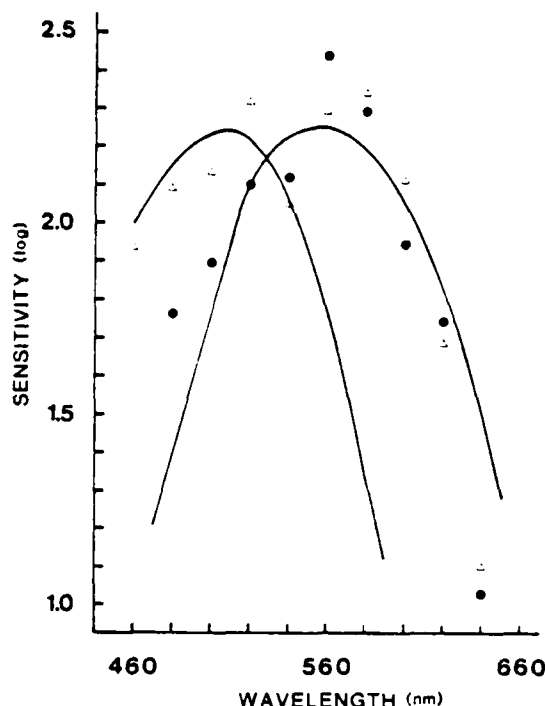


Fig. 6. Spectral sensitivity of ERG (triangles) and scalp recorded VEP wavelets (circles). A criterion latency method was used to estimate sensitivity. Standard CIE spectral sensitivity is represented by the right (photopic) and left (scotopic) solid curves for purposes of comparison.

#### Discussion

In the first experiment of this study, a procedure was developed for recording wavelets from the scalp. The rather stereotypic wavelet repetition rate of 100 Hz permitted the use of relatively narrow band analog filters. By using active filters rather than passive filters usually packaged with preamplifiers, we were able to produce greater attenuation of lower frequency components while maintaining a 60–200 Hz bandpass that we found produced no measurable distortion at 100 Hz. Wavelets can thus be measured with sufficient reliability for additional normative and clinical studies.

Wavelets were usually found 30–40 msec following the onset of a light flash, raising a possibil-



ity that the earliest wavelets are of subcortical, possibly retinal, origin. Reports from other laboratories of wavelets occurring as early as 20 msec (Cracco and Cracco 1978; Harding and Rubenstein 1980) further reinforced this hypothesis. The least interesting finding would be that the approximately 1  $\mu$ V early wavelets are ERG wavelets volume conducted from the retina. Accordingly, Siegfried and Lukas (1981) addressed this possibility. They found that wavelets recorded between  $O_2$  and  $C_2$  which occurred after 50 msec had different repetition rates and relations to retinal illuminance than ERG wavelets. Refinements in the recording techniques have permitted us to measure smaller amplitude, earlier wavelets. With different experiments and a number of subjects we verified Siegfried and Lukas' (1981) conclusions that wavelets recorded between  $O_2$  and  $C_2$  are not passively conducted from the retina.

The difference in the spectral sensitivity of ERG wavelets and VEP wavelets recorded between  $O_2$  and  $C_2$  confirms that ERG wavelets were not measured at the occiput. The spectral sensitivity of wavelets measured between  $O_2$  and  $C_2$  was found to differ from that of ERG wavelets in that ERG wavelets exhibited relatively greater sensitivity to blue light, a result that could be at least partly explained by greater scatter of shorter wave length light in the eye (Graham 1965) and by the sensitivity of the ERG to peripheral retinal stimulation. The occipital wavelets had clearly photopic spectral sensitivity, as do VEP slow waves recorded at this location.

The topography study produced no evidence for retinal potentials near  $O_2$ ,  $O_1$  or  $O_2$ . With more lateral and anterior electrode placements ( $L_3$ ,  $L_4$ ) however, volume conducted retinal activity may have been measurable in one subject. Rubenstein and Harding (1981) studied volume conduction of retinal slow waves and were unable to measure them in the area just above the ear. Reports that optic nerve damage affects early potentials recorded from lateral scalp locations while leaving the ERG, including ERG wavelets, intact tend to indicate that subcortical potentials are measurable at these lateral locations (Rubenstein and Harding 1981; Siegfried 1981). However, we were unable to reliably measure these early potentials in the 3

subjects tested in the present topography study.

Wavelets recorded from the posterior regions of the scalp prior to 70 msec after flash onset are apparently generated from the region of the occipital pole of the cerebral cortex rather than from diffuse cortical or subcortical areas. The amplitudes of these wavelets reached a maximum at the occipital region and when adjacent bipolar electrode pairs were used, the wavelet polarities inverted as the pairs were moved across this region.

Having established that wavelets measured between  $C_2$  and  $O_2$  are likely of cerebral genesis, we turn to differences between cortical wavelets and P100. Although the topography study localized maximum wavelet and P100 amplitudes in the region of  $O_2$ , close inspection of Figs. 4 and 5 reveals systematic differences between wavelet and P100 maxima in some subjects; moreover, when adjacent bipolar pairs of electrodes were used, the wavelets inverted in polarity at a different location than P100 in one subject. In the earlier normative study, as the retinal illuminance increased the latency to P100 decreased, as did the latency of wavelets; however, P100 reached an apparent asymptote at a lower illuminance than did the wavelets, with the latter still decreasing in latency with the maximum  $10^{4.9}$  trolands retinal illuminance. Cortical wavelets and P100 apparently have different neurogeneses. The significance of these differences remains obscure.

Certain properties of the cortical wavelets indicate their potential as possible indices of early cortical processing of visual information. Their early latencies imply that very early cortical processing is reflected by their wave forms. Peak latencies of wavelets occurring before 70 msec do not systematically vary across electrode positions. After 70 msec, however, the wavelet latencies were more variable from electrode position to electrode position, probably due to intrusions of potentials from areas beyond the circumstriate cortex. It follows that early wavelets are local activities in the striate and circumstriate cortex that occur before the visually induced activity becomes widely disseminated among visual areas in the parietal cortex. Wavelets occurring before 70 msec, therefore, are the earliest visual evoked cortical potentials that can be reliably recorded from the scalp

in man. As such, their wave forms reflect the earliest cortical processing of visual information.

### Summary

Low amplitude high frequency wavelets have been demonstrated to be ubiquitous in the visual system of animals and are observed in the ERG of man. Wavelets have also been observed superimposed upon large slow waves obtained from electrodes on occipital scalp. Presently, the rather stereotypic wavelet repetition rate permitted the use of active analog filters tuned to 100 Hz, with a 60–200 Hz bandpass which produced no measurable distortion at 100 Hz. With this method we recorded a series of wavelets in 15 of 16 subjects that usually began from 35 to 40 msec following the onset of a  $10^4$  troland,  $25^\circ$  visual angle 100 msec flash. We then sought to determine the origin of these wavelets. Wavelets recorded between occiput ( $O_z$ ) and vertex ( $C_z$ ) had photopic spectral sensitivity that differed from that of ERG wavelets simultaneously recorded. Moreover, in a topographical study, wavelets recorded between  $C_z$  and various lateral positions reached a maximum at  $O_z$ ; and when adjacent bipolar electrode pairs were used, wavelet polarities inverted as pairs were moved across the occipital region. Thus wavelets recorded between 35 and 70 msec were likely generated from occipital cortex rather than retinal, subcortical, or diffuse cortical sites. In addition, the topographical distribution of slow wave ('P100') and wavelets differed. Wavelet latencies had a different relation to retinal illuminance than P100 latencies, suggesting that P100 and wavelets have different neurogeneses. Wavelets recorded between  $O_z$  and  $C_z$  thus reflect the earliest cortical visual processing recorded in man.

### Résumé

#### *Origine des oscillations dans le potentiel évoqué visuel*

Des oscillations de faible amplitude et de fréquence élevée ont été trouvées un peu partout dans

le système visuel de l'animal, ainsi que dans l'ERG de l'homme. Elles ont également été observées, chevauchant les ondes lentes et amples recueillies par électrodes de scalp occipital. Dans ce travail et en tenant compte du caractère de répétition stéréotypé de ces ondes, on a utilisé un filtre analogique actif, accordé à 100 Hz, avec bande passante de 60–200 Hz (ne produisant aucune distortion mesurable à 100 Hz). Avec cette technique, on a recueilli une série de telles oscillations chez 15 sujets sur 16; celles-ci débutaient généralement 35–40 msec après l'installation d'un flash de  $10^4$  trolands, d'angle visuel de  $25^\circ$ , et 100 msec de durée. On s'est ensuite appliqué à déterminer leur origine. En dérivation entre occipitale  $O_z$  et vertex  $C_z$ , elles ont témoigné d'une sensibilité spectrale photopique, différente de celle de l'ERG enregistré en même temps. En outre, une étude topographique a montré que les oscillations recueillies entre  $C_z$  et diverses positions plus ou moins latérales atteignaient un maximum à  $O_z$ . En utilisant des paires d'électrodes bipolaires adjacentes, les oscillations s'inversaient lorsque les couples d'électrodes étaient déplacés le long de la région occipitale. Ainsi les oscillations recueillies entre 35 et 70 msec naissaient-elles, vraisemblablement à partir du cortex occipital, plutôt qu'à partir de la rétine ou de sites sous-corticaux, ou de sites corticaux diffus. De plus, leur distribution topographique différait de celle de l'onde lente (P100). Quant à leur latence, elle avait avec l'éclairement rétinien une relation différente de celle de l'onde P100, ce qui suggère que les générateurs des deux phénomènes sont distincts. Ces oscillations, ainsi recueillies entre  $O_z$  et  $C_z$ , traduisent ainsi le processus cortical le plus précoce que l'on puisse recueillir chez l'homme.

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